FORMATION AND DEVELOPMENT OF BEACH CUSPS ON DEL MONTE BEACH, MONTEREY, CALIFORNIA

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NAVAL POSTGRADUATE SCHOOL
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THESIS

FORMATION AND DEVELOPMENT OF BEACH CUSPS
ON
DEL MONTE BEACH, MONTEREY, CALIFORNIA

by

Jeffrey George Bodie

September 1974

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Cusp spacing was found to be a function primarily of wave height (energy) and wave period. Regularity of the wave regime during formation was found to result in uniform cusp spacing.

Little migration was observed in mature cusps, and large changes in the wave regime or beach conditions were required to alter the cusp profiles.

The action of large wind waves, storm surges, and breakers, was observed to destroy beach cusps.

Formation and Development of Beach Cusps
on
Del Monte Beach, Monterey, California

by

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I. INTRODUCTION

A. DESCRIPTION OF THE PROBLEM

The study of beach cusps provides an excellent example of the difficulty experienced in attempting to parameterize natural phenomena. Several early researchers attempted to describe cusp formation in terms of only one or two variables, but historical development has tended to emphasize the importance of a number of variables. Opinion is still divided with respect to the order of importance of various parameters and to their role in the sequential history of cusp development. To an observer, cusps appear as crescent-shaped, nearly semicircular, cutouts in the beach face tapering to a point seaward and aligned nearly parallel to the surf line. The triangular points are referred to as the horns, and the semicircular cutout as the bay. The actual form of a given set of cusps may vary from the idea mentioned above and the systematic recurrance of horn-bay-horn will often be the best indication that cusps are present. An example of cusps formed at the experimental site on Del Monte Beach can be seen in Figure 1.

Evans [1938] developed a classification system for beach cusps as follows:

1. Large capelike storm cusps.
2. Large cusps present as ridges of sand on lake bottoms.
3. Individual cusplike forms resulting from the presence of an obstruction.
4. Very small cusps formed by the onshore slop of a dead sea as it moves on shore.
5. Ideal cusps usually occurring in series and with roughly equal spacing.

Figure 1. Example of beach cusps along Del Monte Beach.

Dolan and Ferm [1968] presented a hierarchy of cusp sizes ranging in width from a few centimeters to 700-1500 m. There is also wide variation in the sediments forming cusps, ranging from fine sand to boulders. The cusps studied in this experiment had an average width of 34 m, and would be considered "ideal" cusps under Evans' classification.

B. OBJECTIVES

The purpose of this study was twofold; first, to quantitatively analyze the parameters affecting cusp formation, and second, to study the migration and temporal history of cusps during cycles from genesis to decay. Of particular interest was the relationship between grain size of the beach sediment and cusp formation. Several separate cycles of cusp growth and dissipation were studied in order to determine factors and patterns significant in cusp migration and variation of cusp development among cycles.

C. REVIEW OF THE LITERATURE

Jefferson [1899] stated that cusps were deltaic patterns formed by the backwash through lines of seaweed and debris of "great waves." The seaweed and debris were deposited by spring tides in a line parallel to the surf and located at the scarp of the berm. Exceptionally large waves surge over the weed line and return seaward through breaks in the line fanning out in a deltaic pattern. This theory was refuted by Branner [1900] following the author's observation of beach cusps on clean beaches where no seaweed line existed. Branner attributed cusp formation to the effect of the interference of two sets of waves of translation upon the beach. Convergence of the wave sets would lead

to a sand build-up or horn, and divergence would result in sand being moved to either side and a bay would be formed. Cusp spacing was determined by the curve of the beach and the angle of intersections of the wave fronts.

Johnson [1909] observed that cusps can form from material ranging from the finest sand to the coarsest cobbles. He further stated that if both coarse and fine material were present, cusps would form from the coarser material. Johnson observed that irregularities in spacing were more predominent in the early stages of cusp development, with a high degree of regularity in spacing characteristic of mature cusps. He judged tidal stage, wind direction, and wave period to have little effect upon cusp formation; the most favorable conditions for cusp development should result from a single series of waves advancing normal to the beach. This theory refuted both those of Jefferson and Branner. The author believed that seaweed ridges were merely an unimportant phase in the formation of some cusps, and that intersecting wave trains would destroy cusps.

Johnson believed that irregular depressions on the beach face were modified by selective erosion of the swash. Accidental favoritism determined which depressions developed to larger proportions. When adjacent depressions were of the same size and stable with respect to the amount of water traversing them, an equilibrium condition resulted. Imperfect and compound cusps were the result of intermediate stages of development. Johnson also stated that any one given set of cusps did not influence its successors. The attack of the swash was believed to be concentrated by the horns upon the heads of the bays.

An interesting departure from previous studies was the observation by Butler [1937] of beach cusps on the shores of Lake Olga, Quebec

formed from boulders ranging in size from pea size to 3 ft (0.9 m) in diameter. The author stated that the dimensions of the boulders and the spacing indicated that wave action was not capable of transporting the materials necessary for formation. This led Butler to conclude that either revison of the literature was necessary or that unusual conditions must have been present in order for the small waves on the lake to effect cusp formation. He postulated that wave erosion of glacial drift could undermine the boulders and cause settling, after which the swash eroded shallow basins flanked by cusp ridges.

Escher [1937] theorized that cusps were formed as a result of erosion from the superposition of progressive and standing waves. The crests of the resulting patterns corresponded to beach rises and the troughs to beach depressions. Escher reported that bays flanked by protruding peninsulas offer favorable conditions for this type of wave patterns.

Shepard [1938] believed that waves lacking the interference of strong tidal currents are favorable for cusp formation. He observed that the cusp formation cycle was more closely related to tidal variation than to changing wave sizes, but did not infer that tides formed the cusps. Rather he believed that cusps disappear during high tidal ranges and reappeared during low tidal ranges.

Evans [1938] stated that cusp formation was a consequence of the size, character, and duration of the incident waves, and that cusp spacing was a function of wave size. A major contribution by Evans was the classification system for cusps described earlier. The author observed a "perfect system" of cusps to form in approximately 100 sec as a result of the parabolic swirl of water running through openings

in sand ridges. He also observed that cusps formed with equal readiness regardless of the angle of wave incidence. The cusp horn indicated the direction of incidence in juvenile cusps. In reference to Butler's work at Lake Olga, Evans [1939] stated that the boulder cusps belonged to his class of "ideal" cusps. He concluded that Butler had underestimated the size and probable transport power of the waves. Drifting ice cakes in spring could have created ridges parallel to the beach necessary for cusp formation. He observed that a considerable number of the Lake Olga boulders were less than 1 ft (0.3 m) in diameter and that 3 to 4 ft (0.9 to 1.2 m) waves present on the lake would have been able to move them.

Bagnold [1940] conducted wave tank experiments on beach formation by waves and concluded that due to losses such as friction and percolation through the sand the mean drag force of the surge on surface material is greater on the uprush than on the outwash. The excess force is balanced by the component of gravity on the sloping beach, with the angle of slope depending upon the ratio of energy dissipated to total energy of the upwash. The proportional loss is greatest at the top of the uprush where the mass of the surge water is essentially zero and the potential energy is greatest. Bagnold concluded that for fine-grained beach material the porosity is small and the loss of energy by percolation is negligible; however, as the grain size increases the loss by percolation becomes appreciable. Bagnold observed the water to be deflected by the cusp horns on the uprush and to return down the center of the bay, this being a contradiction of Johnson's observations.

Kuenen [1948] was one of the first researchers to view cusps as depositional features resulting from selective transportation rather

than erosional features. The author implied this conclusion from observations that cusps are composed of different materials than the remainder of the beach. Kuenen proposed the following sequence of cusp formation:

1. Initially, a regular train of waves impinges upon a smooth beach.
2. Slight depressions are eroded by the backwash.
3. Enlargement of these depressions continues as long as the depth allows sediment transport.
4. Erosion slackens when depth in outer bay approaches a critical limit.
5. Refraction of swash progrades the cusp horns.
6. Larger cusps grow at the expense of smaller ones until critical depth is achieved when this condition is reversed.

Kuenen considered refraction of the swash and fanning out onto the horns as essential in the production of cusps. As can be seen in Figure 2, this contrasts with Bagnold's observations. Kuenen also believed that progressive waves combined with standing waves as proposed by Escher could not be accepted as a cusp producing mechanism until strongly developed standing waves with wavelengths comparable to cusp spacing were documented in nature.

A close correlation was found to exist [King, 1951] between the depth of disturbance of sand on sea beaches and the wave height. The relation was approximately linear and on the order of 1 cm for every 1 ft (0.3 m) of wave height at the breaking point. The coarser the sand, the greater was found to be the depth of disturbance and the percolation. This, in turn, led to a steeper swash slope and greater turbulence. This turbulence is concentrated in a relatively narrow zone and sand is disturbed to a greater depth.

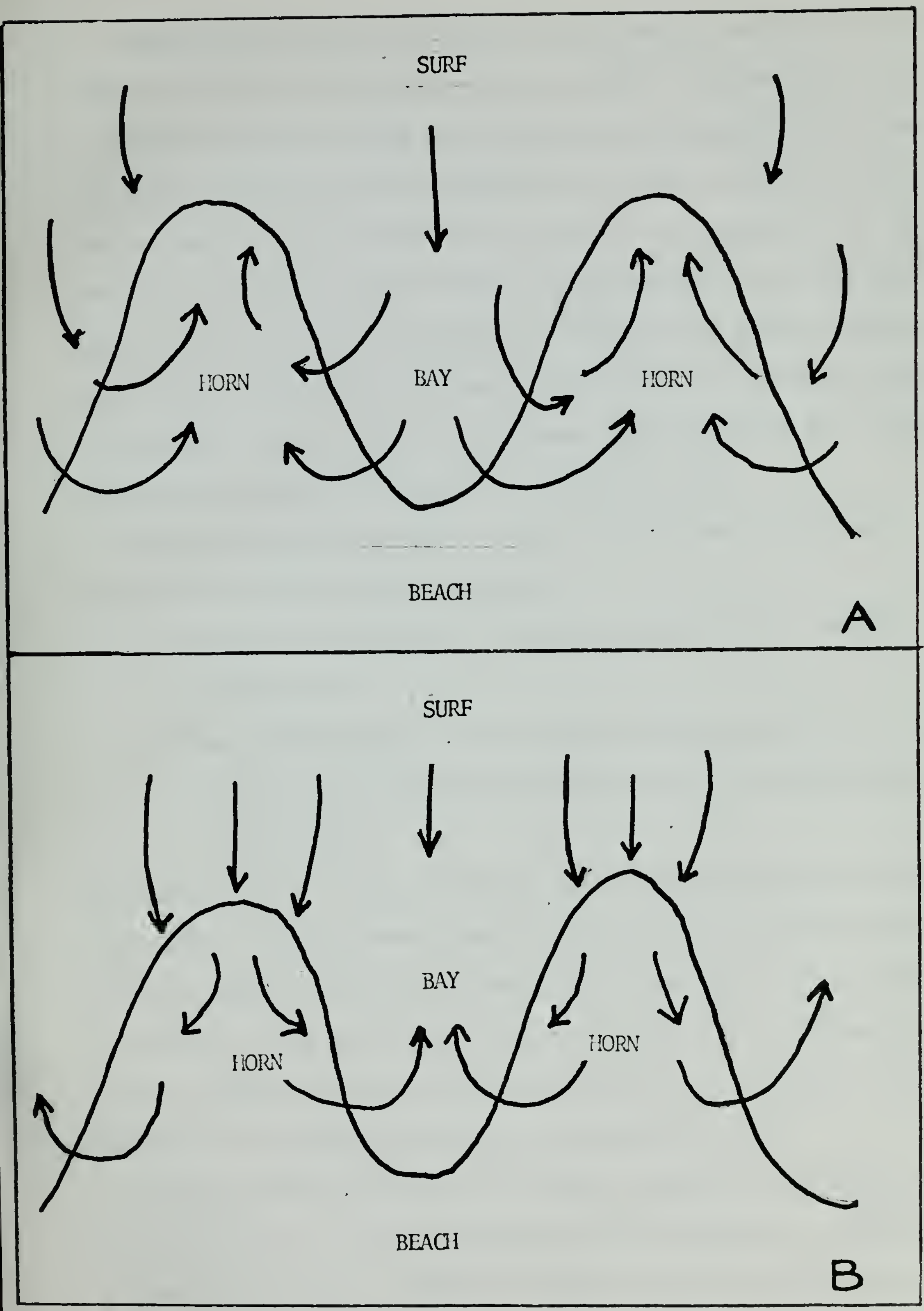


Figure 2. Diagram contrasting swash diffraction patterns as proposed by (A) Kuenen [1948] and (B) Bagnold [1940].

Longuet-Higgins and Parkin [1962] theorized the construction of cusps was due to the occurrence of edge waves. These authors found a close correlation between cusp spacing and wave height, and an even closer correlation between spacing and the width of the swash zone. The presence of an impermeable layer close to the surface in the cusp bays was inferred from observations that permeability was less in the bays than in the horns. The authors observed water motion similar to that noted by Bagnold with refraction from the horns enhancing erosion in the bays. Also noted was the presence seaward of each bay a slight projection and seaward of each horn a definite gully.

Longuet-Higgins and Parkin proposed the following conditions necessary for the formation of cusps:

1. Incident waves should be long-crested and advance perpendicular to the beach.
2. The beach material must be capable of being lifted by the waves and an impermeable layer must exist within a few centimeters of the surface.

Observations by the authors revealed that of several factors the closest correlation existed between cusp spacing and swash length. Both of these parameters have linear dimensions and the ratio was not found to be constant. From this it was inferred that one other fundamental length, perhaps the size of the beach material, was missing. Little correlation was observed between cusp spacing and period.

Flemming [1964] attributed the initial stages of cusp development to the presence of a slight depression in the swash zone, shoreward of a submerged promintory formed by irregular slumping during the formation of the berm. Breaking waves were focused by this promintory to concentrate

maximum energy on the depression. Deposition of material above the waterline occurs on the horns between areas of initial erosion in the embayments. Each horn was located opposite a bay in the submerged beach. These findings agree with those reported by Longuet-Higgins and Parkin [1962].

Flemming also observed a current pattern similar to that reported in this experiment with the swash uprush divided by the horns, flowing around each bay, and uniting to form a single backwash. If the embayment is too large, the backwash streams expend energy before uniting, resulting in the deposition of a secondary cusp. Flemming believed that cusps were initiated randomly where suitable conditions existed, and were built on the irregular remains of their predecessors. Deposition in embayments is dominated by the requirement for a minimum settling velocity, and that on the horns equally by settling velocity and sphericity. Flemming concluded that particles with minimum settling velocities accumulate in the bays while those with slightly higher velocities accumulate on the horns. Size grading is dominated initially by permeability until a layer of sand has been formed, then steeper beaches are built with coarser fractions until only the coarsest remains mobile. This coarse material is then sorted by size and shape, with distance of travel controlled by settling velocity.

Russell and McIntire [1965] found that cusps were composed of different material than the underlying beach. They concluded that cusp horns were depositional features and that sediment on the horns was coarser than that in the bays. Deposition of coarser material on the horns resulted from a decrease in turbulence as the surge washed over the elevations. The initial base level of the bays was established

by backwash flow which possessed sufficient velocity. As cusp development proceeded, however, the velocity of the backwash was not sufficient to entrain any further material. The authors observed cusp spacing to be initially irregular with regularity increasing as growth proceeded. They supported Shepard [1938] in his observation that diagonal wave approach is inimical to cusp development, and that long shore currents commonly destroy cusps. The presence of longshore currents is reflected by rounding of the cusp apices.

According to Russell and McIntire, cusps begin to form during a period of decreasing wave height following a period of high waves which sweep the beach flat and free of debris. They found that shoreward flow exhibits maximum ability to carry large and heavy materials early in the declining phase of wave heights. Conditions favorable for maximum development were believed to occur during the transition from a winter to a summer beach.

A hierarchy of cusp spacing was developed by Dolan and Ferm [1968] in order to represent several orders of shoreline forms. The forms considered are:

1. Cusplet (1.5 m)
2. Typical beach cusps (8-25 m)
3. Storm cusps (70-120 m)
4. Giant cusps (700-1500 m)

Laboratory and field experiments by Bowen and Inman [1969] indicated that combined flow associated with incoming waves, edge waves, and the nearshore circulation may rearrange the beach sediment to produce a regular longshore pattern of beach cusps. They postulated a system of beach cusps could develop where rip currents were present along

steep beaches, and that cusp spacing would be the same as the wave lengths of the nearshore circulation and the predominent edge waves. Slow onshore flow between the rip currents deposits sediment within the surf zone and the seaward flowing rip current erodes a channel for itself. Where the beach slope is small and the surf zone is wide, the cusps formed would be small compared to the rip spacing.

Further work along these lines was conducted by Komar [1971]. He theorized that cusps develop in the lee of rip currents, and that once cusps were produced an equilibrium condition would be achieved and the rip currents disappear. A current cell composed of two rip currents, associated longshore currents, and drift through the breaker zone, as depicted in Figure 3, was proposed. It was expected that cusp development would occur at the center of the cell midway between the rips, but this was not supported in the laboratory and Komar is uncertain if it occurs in nature. Laboratory experiments revealed that cusps formed in the lee of the rips and not in the center of the cell. Apparently a back eddy forms shoreward of the rip which permits deposition of a lee-rip cusp. The critical factor is believed to be the amount of sand deposited vs the amount carried out in the rip. Komar states lee-rip cusps are definitely observed in nature. Following the formation of cusps, an equilibrium condition would be attained in which the longshore currents cease and the rips completely disappear. Equilibrium would be reflected by the presence of small waves at the point of cusps and large waves on embayments as shown in Figure 4.

The author concludes that the two driving forces necessary for development of this type are:

1. A nearshore cell circulation
2. Longshore currents with an oblique wave approach

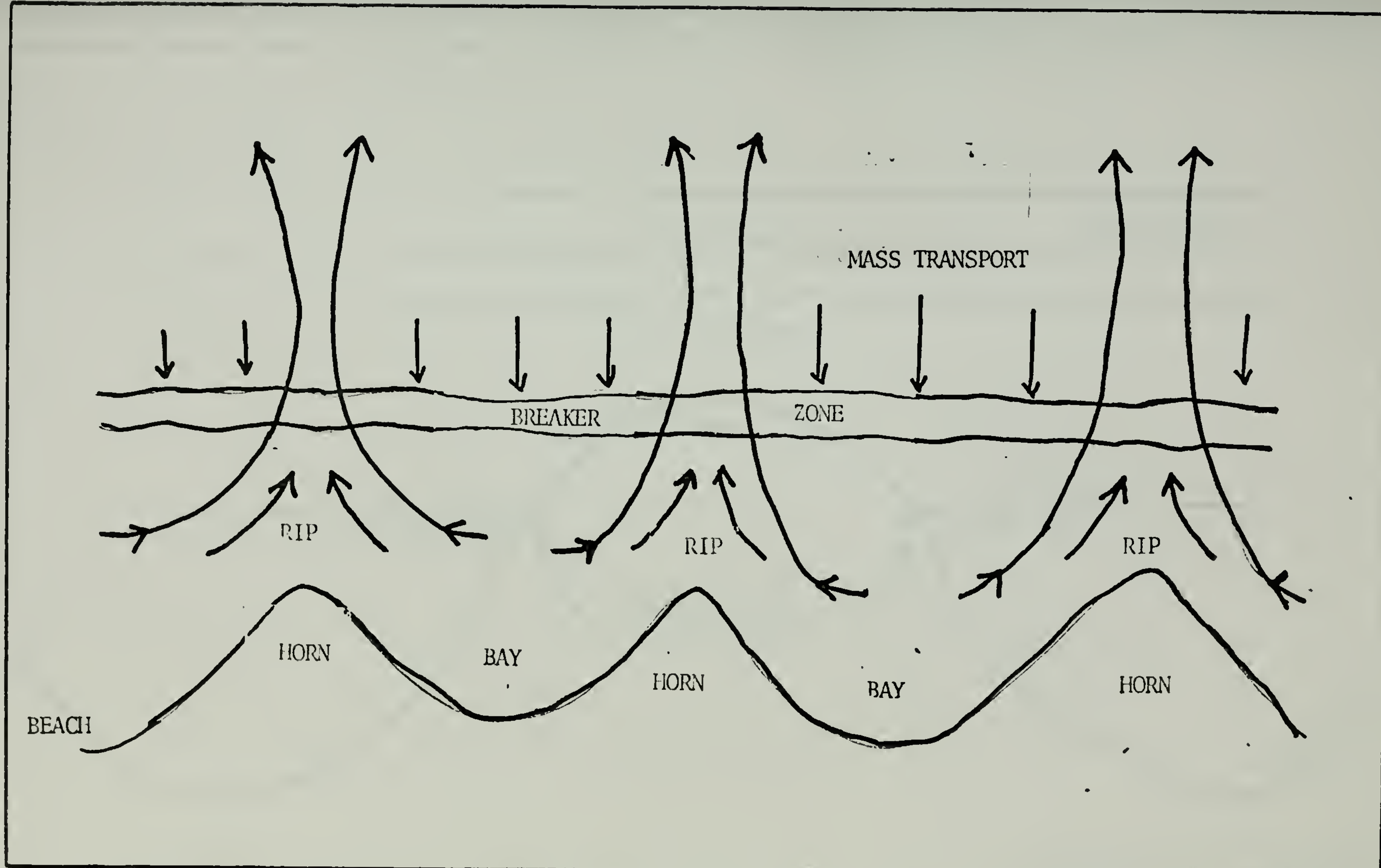


Figure 3. Relation between nearshore rip circulation and beach cusps as proposed by Komar [1971].

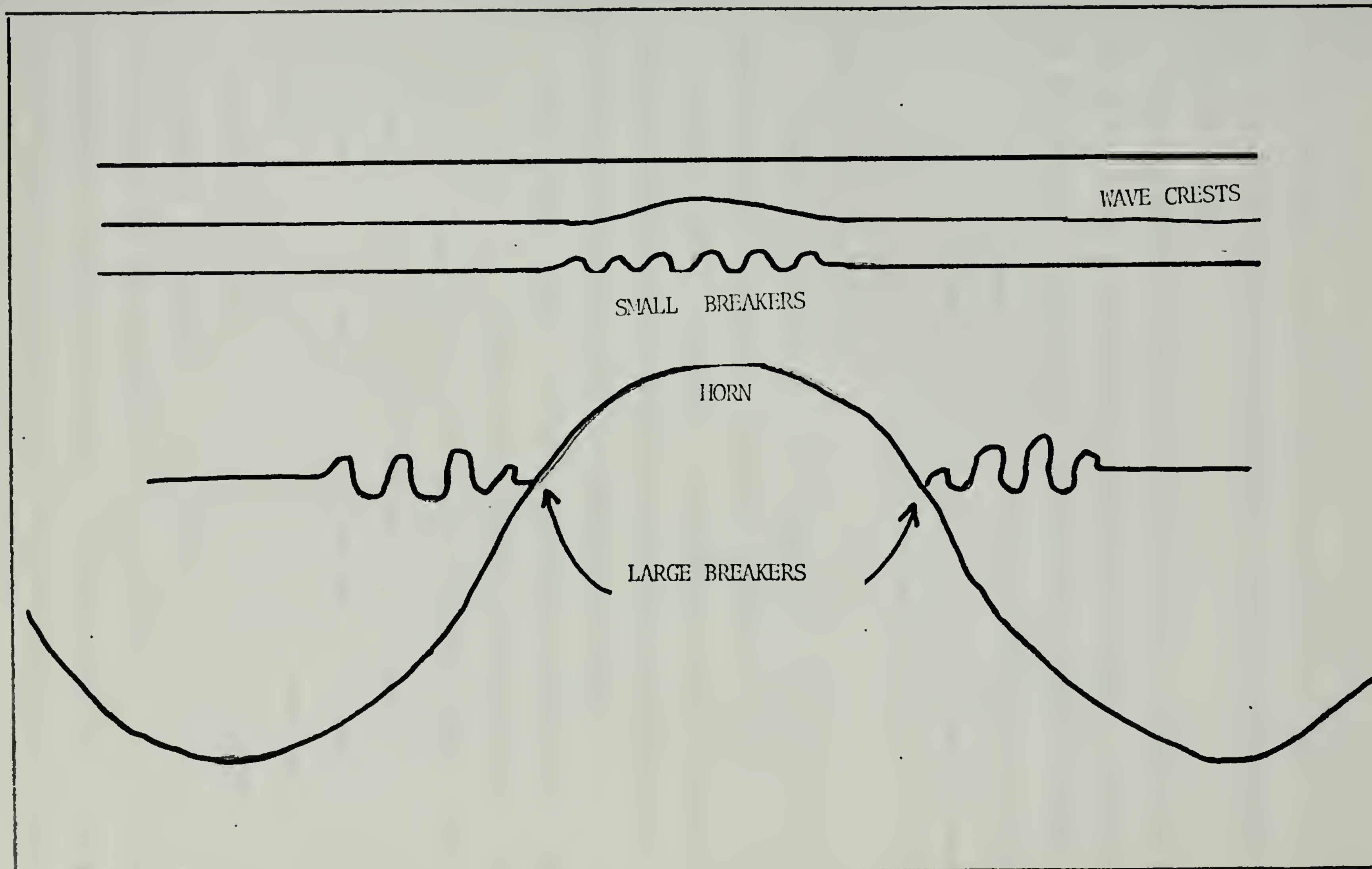


Figure 4. Equilibrium conditions of the nearshore circulation related to beach cusps as proposed by Komar [1971].

Both of these currents balance and cease to exist at equilibrium. The author believes it apparent that some cusps (giant cusps) could form in this manner and that more systematic field study will provide further proof.

Brueggeman [1971] noted that cross-lamination in cusp horns implied an even flow of swash from the horns into the troughs. He also found a direct relation between spring and neap tidal cycles and cusp position for permanent cusps. Cusp apices were found to move shoreward with the approach of spring tides with a corresponding seaward migration occurring in the period before neap tides, with little lateral migration along the beach.

Hardcastle [1973] reported that longshore drift stratification was proportional to the angle of the swell approach, the square root of significant height of the waves, and twice the sine of the angle of approach. Vertical stratification was found to be proportional to frequency and the square root of significant height.

Small scale cusps (11-59 cm) were observed on the shores of Mono Lake, California by Komar [1973]. According to the author, the circulation observed was precisely that described by Bagnold [1940]. Sediment sorting was observed with the coarser material found on the cusps and the finer material in the embayments. Extrapolating his results to ocean beaches, Komar reasons that the most important factor in beach cusp formation is the presence of low, surging waves that do not break at the shoreline. He attributes the lack of cusp formation during breaking wave conditions to the irregularity of waves generated immediately adjacent to the beach. The author stated: ".. no doubt that wave surge was responsible for the generation of the rhythmic

beach cusps." Only indirect evidence for the existence of edge waves could be found at Mono Lake. However, the unusual formation of beach cusps under wave surge, and correspondence in spacing with expected edge wave lengths, led the author to conclude that edge waves were responsible for generation.

Smith [1973] concluded that although cusp spacing is a function primarily of wave height at the time of formation, a delicate balance of wave height, breaker angle, beach slope, and sediment size must be present before formation will occur.

II. DATA COLLECTION

A. LOCATION AND PERIOD OF EXPERIMENT

The experimental site chosen was one that had exhibited a past history of cusp development [Smith, 1973], and provided easy access for observation and data collection. In addition, the existence of a previous data base for this site would allow comparison of results. The time period chosen for the experiment was dictated primarily by the desire to observe sequential cycles of cusp growth and decay. This would require changes in beach conditions and in the wave regime of sufficient magnitude to create and destroy cusps. Observations over several years [R. H. Bourke, personal communication] indicated that semi-permanent cusps were present during the summer months due to relative constancy of conditions. For this reason it was decided to study the winter beach in expectation that winter storms would enhance the transitory nature of cusp formation.

The data collection site selected for this experiment (Figure 5) was in the middle of Del Monte Beach. This location coincides with that of Smith's [1973] Middle Beach. Initial observations with dye markers placed in the surf supported Dorman's [1968] conclusion that the area exhibits virtually no longshore current. Wave refraction studies [J. L. Kiethly, personal communication] indicate a very small breaker angle for waves of the period and direction observed in this study. The average swell observed for this area was from the NNW with a period of 15.0 sec and a significant breaker height of 3.6 ft (1.1 m).

The data collection period was from 24 January 1974 through 3 March 1974 (44 days), and consisted of daily observations. The observation

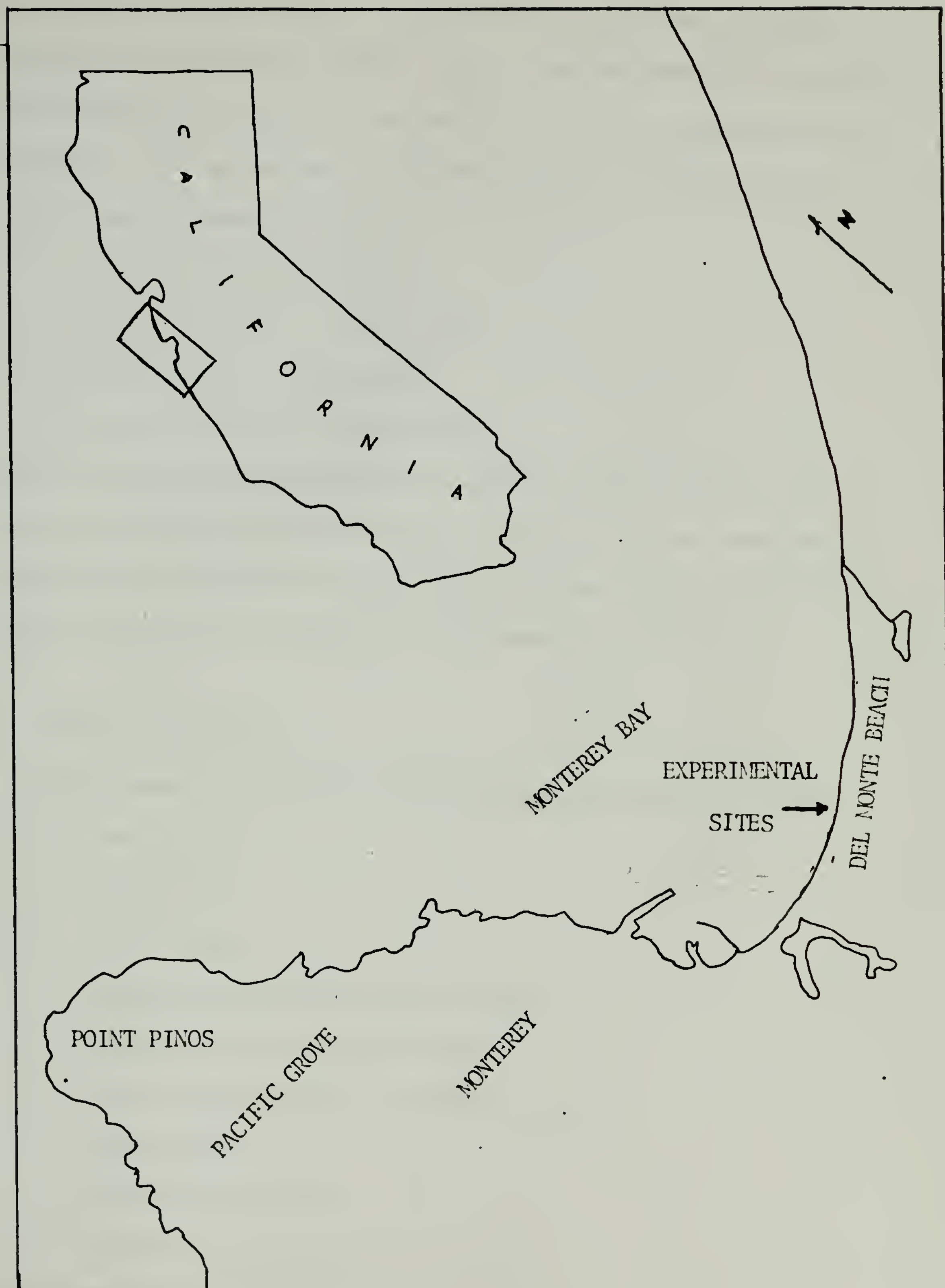


Figure 5. Location of the experimental site (modified from Smith, 1973).

period spanned four complete cusp cycles with intervening periods in which no cusps were present. A cycle was considered to begin with the formation of an embryo horn and to cease when large waves swept the beach clean and no cusps could be observed. The dates of the cycles observed were as follows:

1. Cycle I (23-30 Jan 1974)
2. Cycle II (31 Jan - 1 Feb 1974)
3. Cycle III (4-16 Feb 1974)
4. Cycle IV (20 Feb - 3 Mar 1974)

Daily observations were planned to coincide closely with high tide in order to observe the experimental site during actual development. Although unforseen events occassionally precluded this, observations were taken on each day during the experimental period.

B. PARAMETERS MEASURED

The parameters recorded during this experiment were as follows:

1. Cusp width
2. Cusp depth
3. Cusp movement
4. Relative permeability (horn and bay)
5. Sediment texture (horn and bay)
6. Depth to impermeable layer (horn and bay)
7. Beach slope
8. Width of swash zone
9. Sediment accumulation
10. Height of tide
11. Significant breaker height

12. Wave period

13. Angle of wave incidence

14. Weather information

All parameters were recorded daily with the exception of grain size which was recorded only at periods of significant change in cusp formation. Measurements of applicable parameters were recorded between cycles when no cusps were present. The following definitions when referenced to Figure 6 will serve to familiarize the reader with the nomenclature used in this experiment. The author has attempted to coordinate parameter descriptions with those most commonly found in the literature.

Cusp width was measured from horn to horn, on or close to the apices. Cusp depth was measured in the center of the embayment on the same line used to measure cusp width. Cusp movement was recorded with respect to a pre-determined, fixed, coordinate axis established prior to the experiment. A reference cusp was chosen during the initial phase of each cusp development cycle, and the cusp's longshore and on-shore-offshore movement recorded with respect to this two-dimensional axis.

A plastic tube with a diameter of 2.2 in (6.7 mm) was used to obtain a measure of the relative permeability. The tube was graduated to record the passage of 1 liter of seawater. The tube was inserted a fixed distance into the beach on each occasion and the time required for 1 liter of water to drain into the sand under the influence of gravity was recorded. Due to the pressure generated by the height of the water column, variations in tidal height, and beach water table level, no attempt was made to correlate permeabilities recorded on

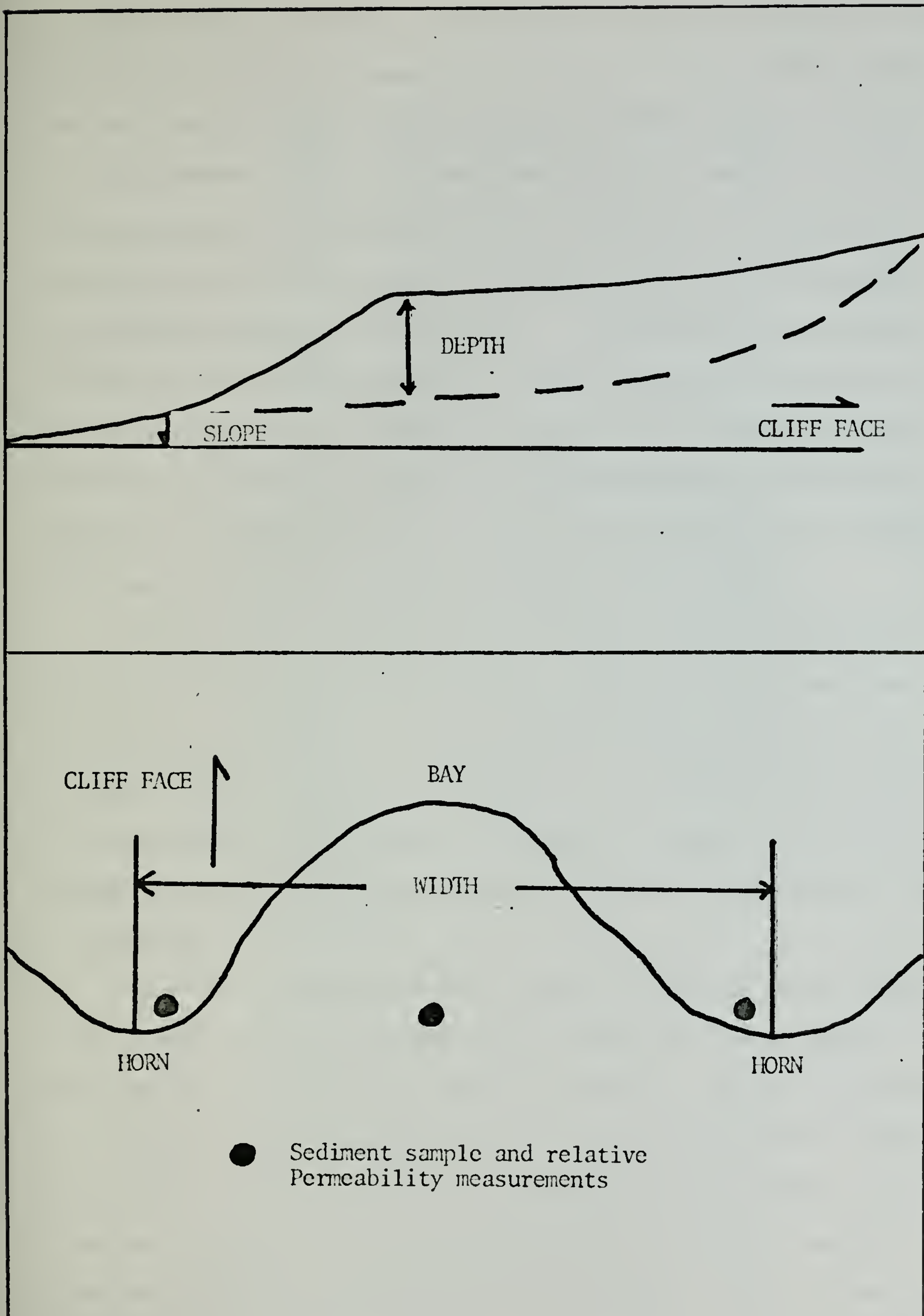


Figure 6. Description of experimental parameters (modified from Smith, 1973).

different days. Depth to the impermeable layer was measured by using body weight to push the measuring staff into the sand. This parameter, as described by Longuet-Higgins and Parkin [1962], defines the depth of the pavement level of the beach and provides a measure of sediment deposited above this pavement level. No measurement of permeability was made to verify the concept of an impermeable layer as described by Longuet-Higgins and Parkin [1962]. The differences in the depth of penetration of the measuring staff were used as an indication of vertical changes in the sediment properties (i.e., bearing strength) which were inferred to represent significant changes in permeability. Thus the term impermeable layer will be used in this paper to indicate the base level of beach sand upon which the cusps develop.

Swash width was measured from the point of maximum uprush of the surge to the low point of the backwash. The slope of the beach was measured at the center of the bay of the reference cusp using a two-armed protractor fitted with a bubble level. Sediment samples were taken from both horn and bay, as indicated by Figure 6. Care was taken to ensure that subsequent samples were taken from the same region of the cusp.

A wave pole graduated in feet was used to estimate breaker heights for a group of 20 waves at each daily observation. These breaker heights were averaged and converted to significant heights by multiplying by a factor of 4/3 to account for the depression of the wave trough below the still water level [U.S. Hydrographic Office, 1958]. The average significant period of the well-defined waves was measured. A mean value was determined from the time required for 5 or 6 such waves to pass a fixed point. A sequence of such averages was obtained until the values were judged to be in good agreement.

Figure 7. Photograph showing stake arrangement for cusp cycles I, II and III.

Sediment accumulation was measured by the use of 1/2 inch (1.3 cm) diameter steel rods calibrated in centimeters and inserted into the beach to a uniform reference level at the beginning of each cusp cycle. Double rows of 10 stakes each with a longitudinal and transverse spacing of 15 ft (4.6 m) between stakes were aligned parallel to the waters edge so as to completely straddle the reference cusp. Figure 7 shows the alignment used for the first three cycles studied. A single row of 20 stakes placed 20 ft (6.1 m) apart was used for sediment accumulation studies during cusp cycle IV in an attempt to span several successive cusps. The stakes were placed at mid-tide level in order to allow coverage by the surge at high tide, but yet not be so close to the waterline that they would be totally submerged.

III. DATA ANALYSIS AND PRESENTATION

A. SEDIMENT TEXTURE ANALYSIS

Sediment samples were oven dried and shaken for 10 minutes on a ROTAP machine. A 0.5 Φ increment was used between each screen in the stack. Fraction weights for each increment were then determined using an electronic balance. Folk and Ward mean grain diameter statistics (Table I) were generated using a library computor program. A trend column was tabulated in order to reflect those pairs of samples in which the grain size of sediment on the cusp horn was greater than that in the embayment. Samples were taken at periodic intervals in each cusp cycle and during the "flat beach" intervals between cycles. During the final phase of the experiment samples were taken from two cusps within the study area.

B. RELATIVE PERMEABILITIES

Relative permeabilities were determined each day, with several exceptions due to equipment failure. The data were normalized by dividing an average permeability calculated for the entire experiment by each individual measurement. For example, a value greater than unity represents a relative permeability greater than the calculated average. A total of 29 pairs of permeability measurements yielded 23 cases (79%) in which relative permeability of the cusp horn was greater than that in the embayment. These data are recorded in Table II. The calculated average permeability for the 29 pairs of observations was determined to be 485.2 sec.

TABLE I

RESULTS OF SEDIMENT SIZE ANALYSIS

Date	Location	Mean Grain Diameter (mm)	Description	Trend
1/25/74	Bay	0.234	FS	
1/25/74	Horn	0.246	FS	+
1/28/74	Bay	0.258	MS	
1/28/74	Horn	0.226	FS	-
2/2/74	No Cusps	0.255	MS	
2/3/74	No Cusps	0.248	FS	
2/8/74	Bay	0.241	FS	
2/8/74	Horn	0.244	FS	+
2/10/74	Bay	0.246	FS	
2/10/74	Horn	0.255	MS	+
2/12/74	Bay	0.244	FS	
2/12/74	Horn	0.258	MS	+
2/13/74	Bay	0.243	FS	
2/13/74	Horn	0.260	MS	+
2/17/74	No Cusps	0.291	MS	
2/18/74	No Cusps	0.277	MS	
2/19/74	No Cusps	0.291	MS	
2/21/74	Bay A	0.271	MS	
2/21/74	Horn A	0.244	FS	-
2/24/74	Bay A	0.260	MS	
2/24/74	Horn A	0.285	MS	+
2/24/74	Bay B	0.273	MS	
2/24/74	Horn B	0.269	MS	-
2/26/74	Bay A	0.241	FS	
2/26/74	Horn A	0.258	MS	+
2/27/74	Bay A	0.253	MS	
2/27/74	Horn A	0.273	MS	+
2/27/74	Bay B	0.271	MS	
2/27/74	Horn B	0.257	MS	-

TABLE I

RESULTS OF SEDIMENT SIZE ANALYSIS (Continued)

Date	Location	Mean Grain Diameter (mm)	Description	Trend
3/1/74	Bay A	0.234	FS	
3/1/74	Horn A	0.250	FS	+
3/3/74	No Cusps	0.275	MS	
3/3/74	No Cusps	0.251	MS	

FS = Fine Sand
MS = Medium Sand

*Horn Diameter > Bay = +
*Bay Diameter > Horn = -

TABLE II

RELATIVE PERMEABILITIES

Date	Relative Permeability (Horn)	Relative Permeability (Bay)
1/24/74	1.2	1.1
1/25/74	1.0	0.90
1/26/74	1.1	0.99
1/27/74	1.2	0.84
1/28/74	1.5	1.2
1/29/74	1.5	1.0
1/30/74	1.3	1.1
1/31/74	1.0	1.0
2/1/74	0.97	1.1
2/8/74	0.86	0.84
2/9/74	1.1	0.95
2/10/74	0.95	0.93
2/11/74	0.93	0.91
2/12/74	1.1	0.84
2/13/74	1.2	1.1
2/14/74	1.2	0.90
2/15/74	0.93	0.90
2/16/74	1.1	0.67
2/24/74	0.82 Cusp A	0.56 Cusp A
2/24/74	0.99 Cusp B	0.88 Cusp B
2/25/74	1.4 Cusp A	1.0 Cusp A
2/25/74	0.99	0.85
2/26/74	1.4	1.1
2/27/74	1.3 Cusp A	1.1 Cusp A
2/27/74	1.1 Cusp B	1.1 Cusp B

TABLE II

RELATIVE PERMEABILITIES (Continued)

Date	Relative Permeability (Horn)	Relative Permeability (Bay)
2/28/74	1.4 Cusp A	1.6 Cusp A
2/28/74	1.0 Cusp B	1.3 Cusp B
3/1/74	1.7	1.3
3/2/74	1.2	1.3

C. MULTIPLE REGRESSION ANALYSIS OF CUSP WIDTH VS MEASURED PARAMETERS

Subprogram Regression from the Statistical Package for the Social Sciences (SPSS) was used to perform a stepwise multiple regression on the measured parameters with cusp width as the dependent variable. This method recursively constructs a prediction equation one variable at a time. At each step the optimum variable is selected until the significance of that variable, as measured by the F statistic is too small for further computations. The advantages of the SPSS package which prompted its choice over the BMDO2R program used by previous researchers [Smith, 1973] are the ability to process "missing data," and more readily understandable plain-language inputs.

Initially, stepwise inclusion of variables was performed with each variable entered one at a time as long as the variable made a significant contribution to the regression equation. This technique was used to aid in selecting parameters for further analysis. The parameters thus selected were the following:

1. Significant breaker height (H)
2. Wave Period (T)
3. Beach slope (S)
4. Cusp depth (D)
5. Width of swash (WS)
6. Grain size horn (GSH)
7. Permeability horn (PH)
8. Cusp width (W) (dependent variable)

In addition, the following variables were transgenerated for use in subsequent analyses:

1. Swash width times slope (WSXS)
2. Wave frequency (1/T)

3. Breaker height divided by slope (H/S)

4. Reciprocal slope (1/S)

5. Energy (H^2)

6. Energy divided by slope (H^2/S)

Various combinations of these parameters were then processed in an attempt to derive the best regression equation relating the variables. A "multiple inclusion mode" was used in order to "force" all of the desired variables in each combination into the regression analysis at one step.

The data were then subjected to two filtering processes and the above analysis repeated. Filtering consisted of analyzing data only from those days on which a significant change in the dependent variable (cusp width) was recorded. The amount of change for the respective filters was:

1. Filter #1 - 2 ft change in cusp width

2. Filter #2 - 4 ft change in cusp width

These results were then compared with results obtained by Smith [1973] in a previous study on Del Monte Beach. In an attempt to generalize the preceding results, Smith's data were combined with the data from this study and the combined data base subjected to regression analysis as described above. Filter #1 was applied to the combined data set. The results of the regression analysis are summarized in Table III. The multiple regression coefficients listed provide a measure of the relationship existing between the variables. The closer the coefficient is to unity, the better the linear relationship between the variables. Even when this coefficient is zero, it is possible for non-linear relationships to exist.

TABLE III

REGRESSION COEFFICIENTS

Parameters	All Data	Filter #1	Filter #2	Smith 1973	Combined Data
H	.1344	.3096	.2348	.5591	.2708
H^2	.2044	.3398	.2805	.5242	.2474
T	.3371	.1950	.2930	.4785	.3421
H,S	.1364	.3158	.2383	.5659	.2807
H^2, 1/S	.2061	.3468	.2806	.5251	.2636
H, 1/S	.1390	.3172	.2350	.5596	.2880
H^2/S	.1905	.3081	.2554	.4839	.2716
H/S	.1111	.2602	.2607	.4176	.2879
T, 1/S	.3374	.1950	.3207	.5157	.3428
T, H, 1/S	.4080	.3825	.4058	.6041	.4175
T, H, S	.4086	.3825	.2930	.5834	.4164
H, D, 1/S	.1818	.3175	.3589	.6861	.3019
D, T, 1/S	.3605	.2062	.4098	.6579	.3590
H, D, S, T, 1/S	.4165	.3887	.5363	.7030	.4340
T, H, WSXS	.4565	.3913	.2930	1	.4251
S, H^2, H, 1/T	.5635	.4653	.5483	1	.4550
H/S, S, H, PH, GSH, H^2	.5496	2	2	1	2
H, 1/S, 1/T	.4248	.3828	.4036	1	.4345
H, 1/T, H^2/S	.4799	.4055	.4557	1	.4345
H^2, H, 1/S	.4419	.3794	.3922	1	.3031

1 This combination not analyzed by Smith

2 Insufficient data for analysis

The results indicate that no simple combination of parameters produces a satisfactory equation. The most satisfactory combination to fit the data is:

$$W = 65 + 11\,H^2 - 23\,H - 0.53S - 289\ (1/T)$$

W = Cusp width (m)

H^2 = Energy (m^2)

H = Significant breaker height (ft)

S = Beach slope (degrees)

$(1/T)$ = Frequency of incident waves (sec^{-1})

An attempt was made using subprogram Regression to investigate possible non-linear interactions of the measured parameters. The natural logarithms of significant breaker height, beach slope, cusp depth, and wave period were generated for the combined data base, and various combinations of these parameters were analyzed using a multiple inclusion mode. The best equation generated in this manner was the following:

$$W = 65.9 + 1.5S + 3.4H - 94.4\ (1/T)$$

W = Cusp width (m)

H = Significant breaker height (m)

S = Beach slope (degrees)

$(1/T)$ = Wave frequency (sec^{-1})

This equation has an R^2 value of 0.21 indicating no significant non-linear relationships exist between the parameters tested.

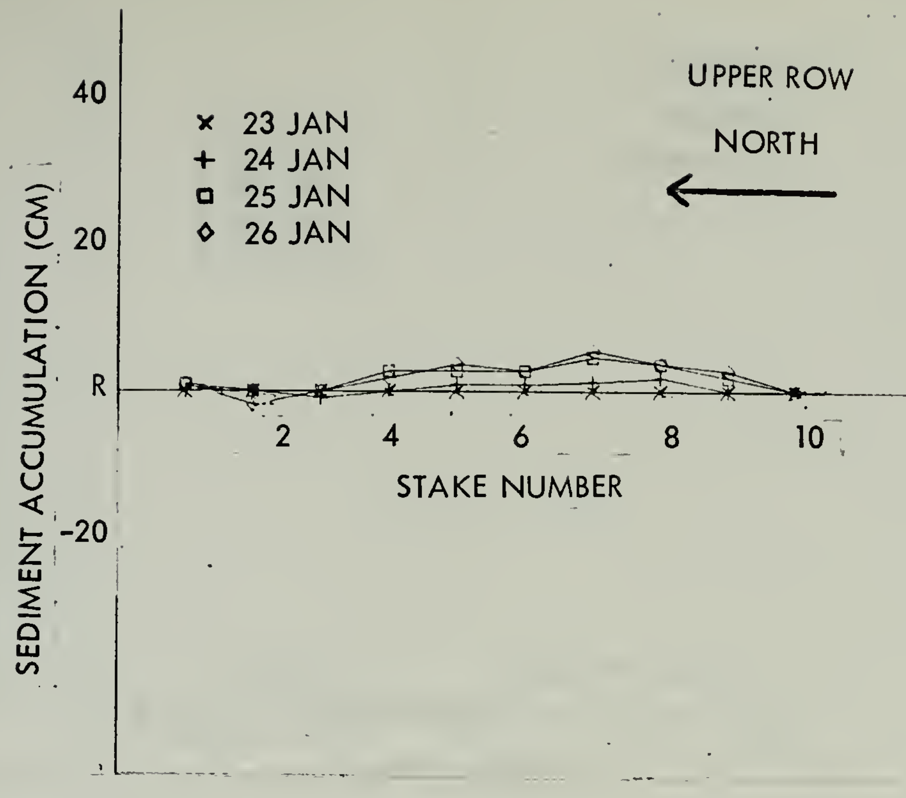
No satisfactory equation relating cusp width to a pair of variables as proposed by Smith was found. The results of analysis performed using the combined data base show regression coefficients significantly lower than those obtained by Smith. This is attributed to the effect of data

from this present experiment which comprised 47% of the combined total. Due to relatively stable wind and wave regimes during the 1974 experimental period, the measured parameters did not exhibit the variability experienced during the 1973 experiment. The absence of significant change in the independent variables is reflected in the reduced regression coefficients. It is therefore believed that the results obtained have validity only for the experimental site studied in this experiment and do not constitute a general equation.

The square of the regression coefficient (the R^2 value) indicates the percentage of cases for which the computed regression equation can satisfactorily predict as opposed to that which would be expected were the parameters randomly related. The R^2 value provides a measure of how well the equation "explains" the variation of the dependent variable. The R^2 value for the equation developed in this study indicates the equation is successful in explaining only 32% of such cases. It is evident that a fundamental parameter has been omitted from consideration. Longuet-Higgins and Parkin [1962] hypothesized that this parameter was mean grain size, an hypothesis not supported by the analysis in this study. No completely satisfactory explanation could be developed for the apparent preference of mean grain size and permeability of the cusp horn vice cusp bay in the regression analysis. However, negligible differences between mean grain size on the horn and in the embayment coupled with the limited number of sediment samples processed are possible reasons. Because no previous data on grain size were available for comparison, the parameter was suppressed in the majority of cases. A qualitative discussion of the effects of mean grain size and permeability will be presented in subsequent sections of this paper.

D. SEDIMENT ACCUMULATION AND CUSP PROFILES

From data based upon the stake measurements a record of change in beach profile during each of the four cusp cycles studied was generated in graphical form using the CALCOMP plotter. This record traces the growth and decay of the reference cusps. Accumulations were plotted with respect to a zero reference axis established for each cycle when the stakes were inserted in the beach. This should not be confused with the pavement or impermeable layer which lies below the surface at varying depths according to the amount of sediment deposited. The depth to this impermeable layer is noted in the legend accompanying Figures 8 through 16.



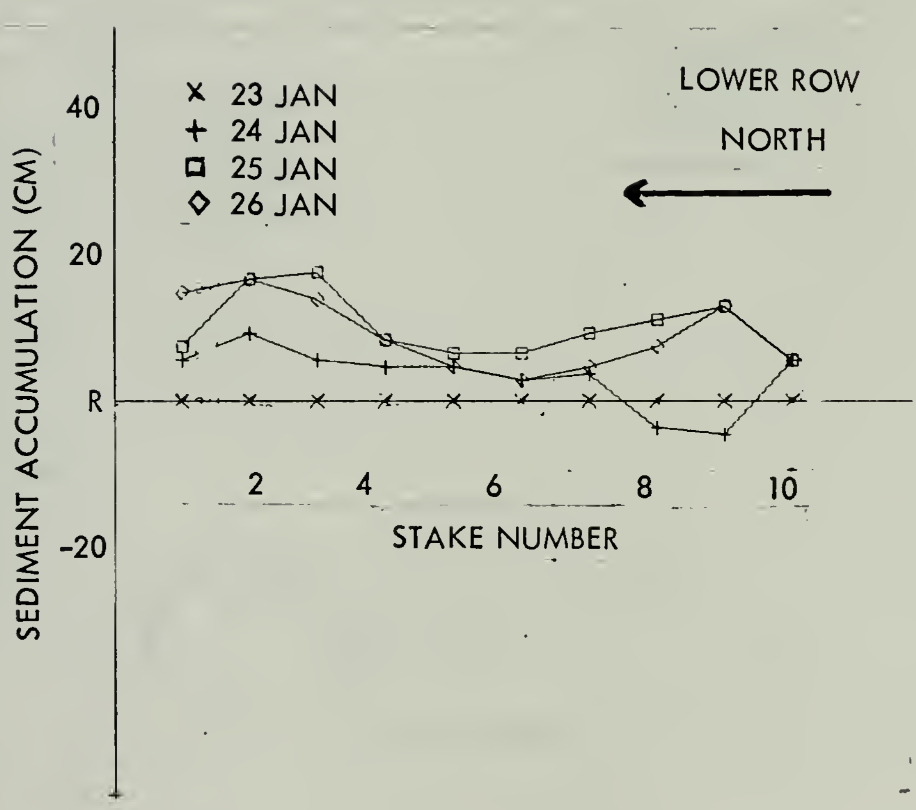


Figure 8. Sediment accumulation profiles for cusp cycle I (23-26 Jan 1974). Stake spacing 15 ft (4.6 m). Depth from reference level (R) to impermeable layer 11 in (28 cm).

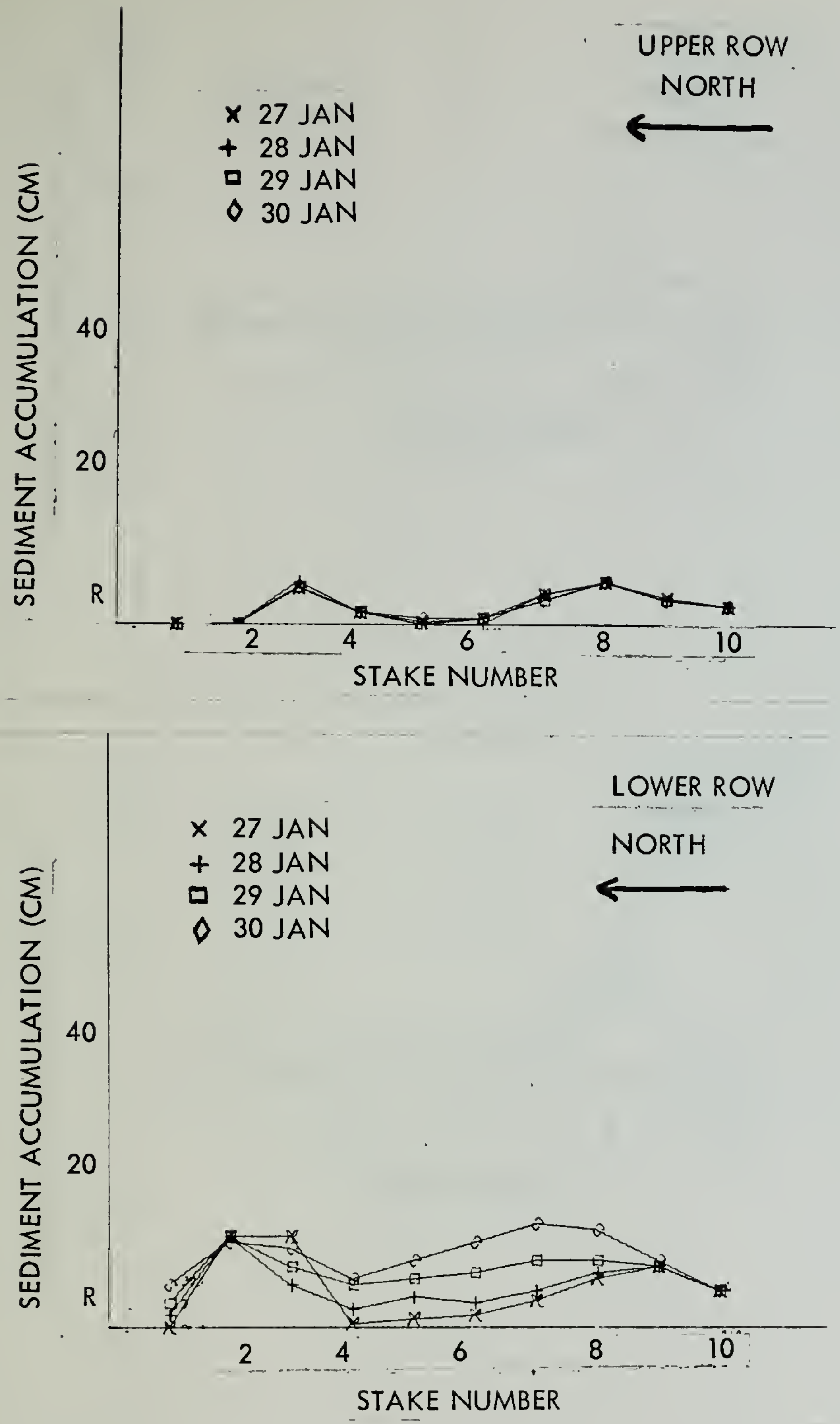
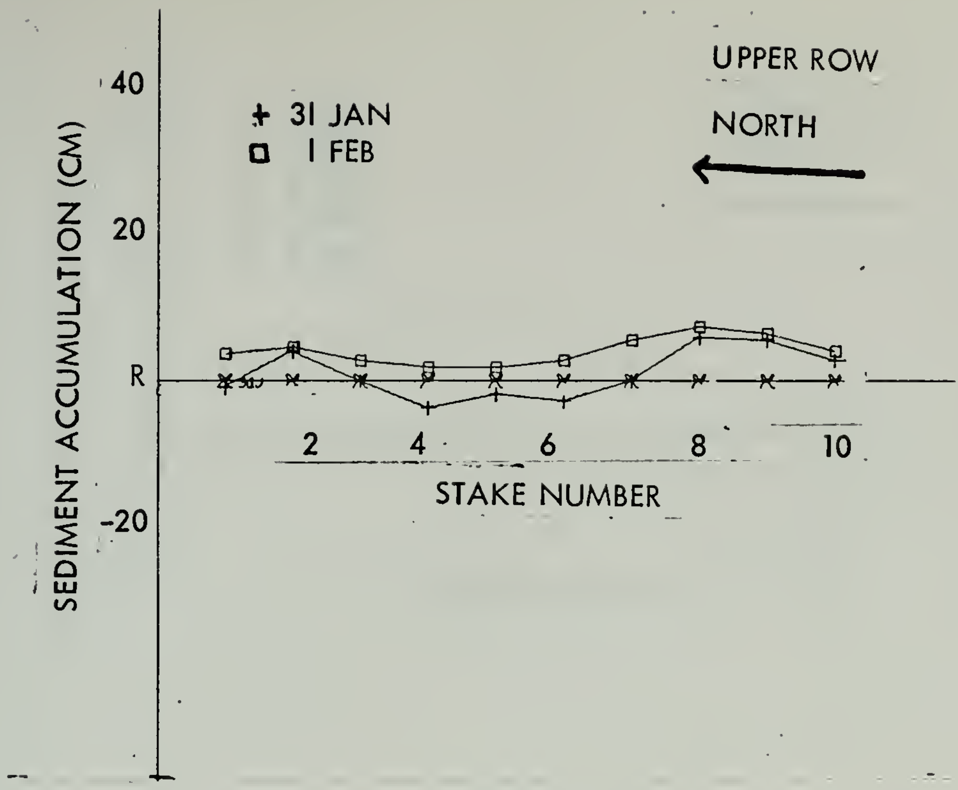


Figure 9. Sediment accumulation profiles for cusp cycle I (27-30 Jan 1974) Stake spacing 15 ft. (4.6 m). Depth from reference level (R) to impermeable layer 11 in (28 cm).



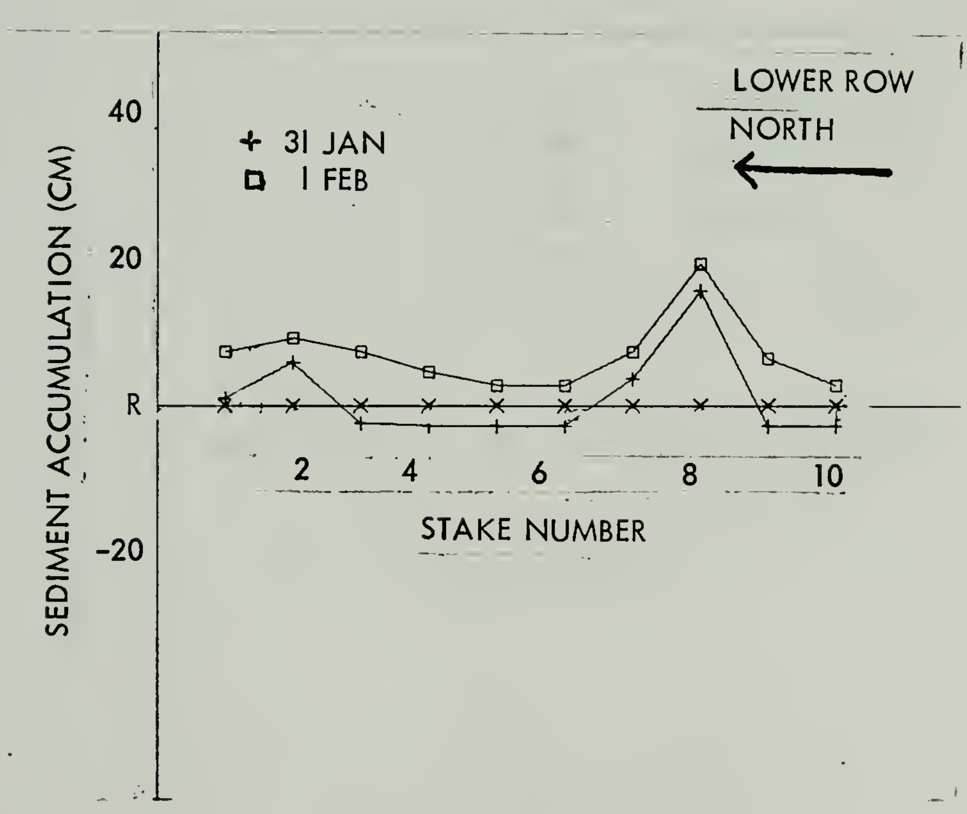
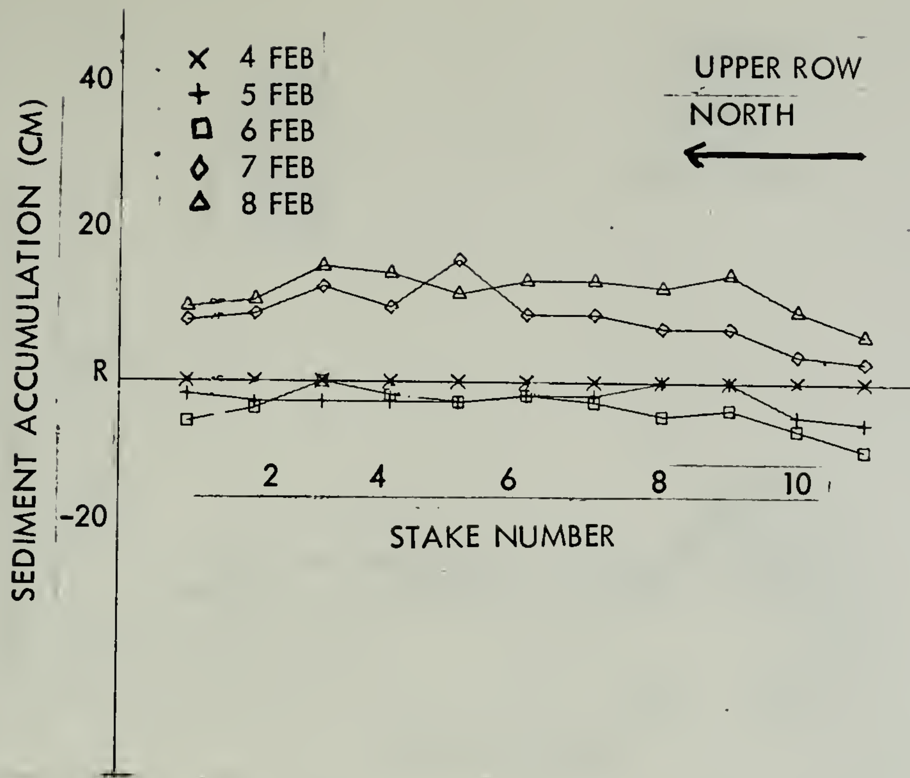


Figure 10. Sediment accumulation profiles for cusp cycle II (31 Jan - 1 Feb 1974). Stake spacing 15 ft (4.6 m). Depth from reference level (R) to impermeable layer 7 in (18 cm).



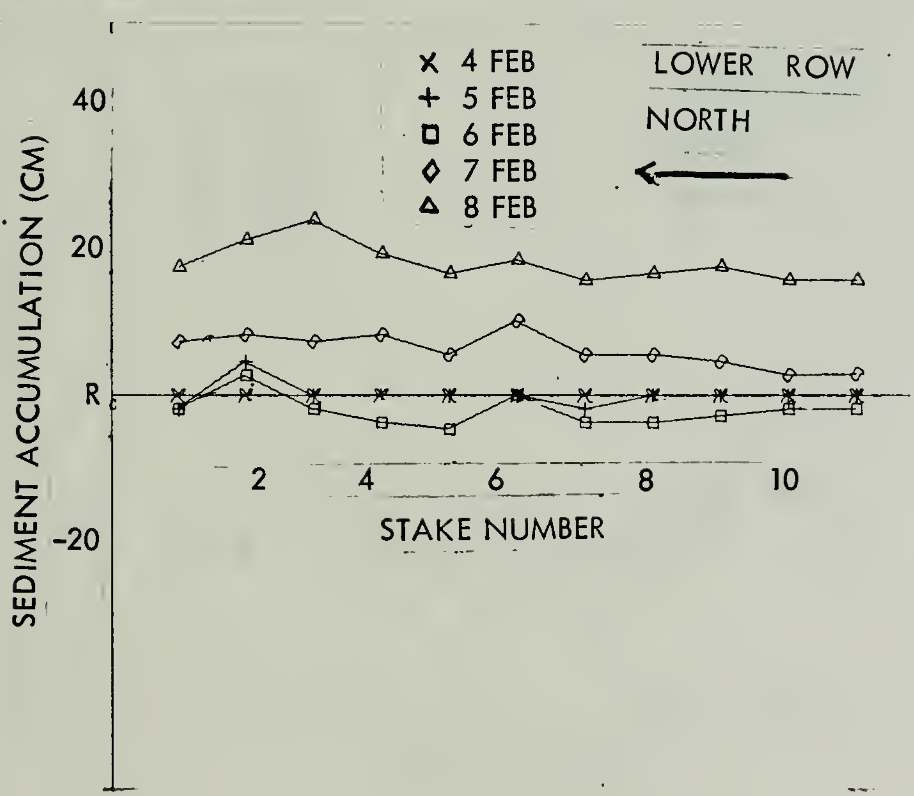


Figure 11. Sediment accumulation profiles for cusp cycle III (4-8 Feb 1974). Stake spacing 15 ft (4.6 m). Depth from reference level (R) to impermeable layer 7 in (18 cm).

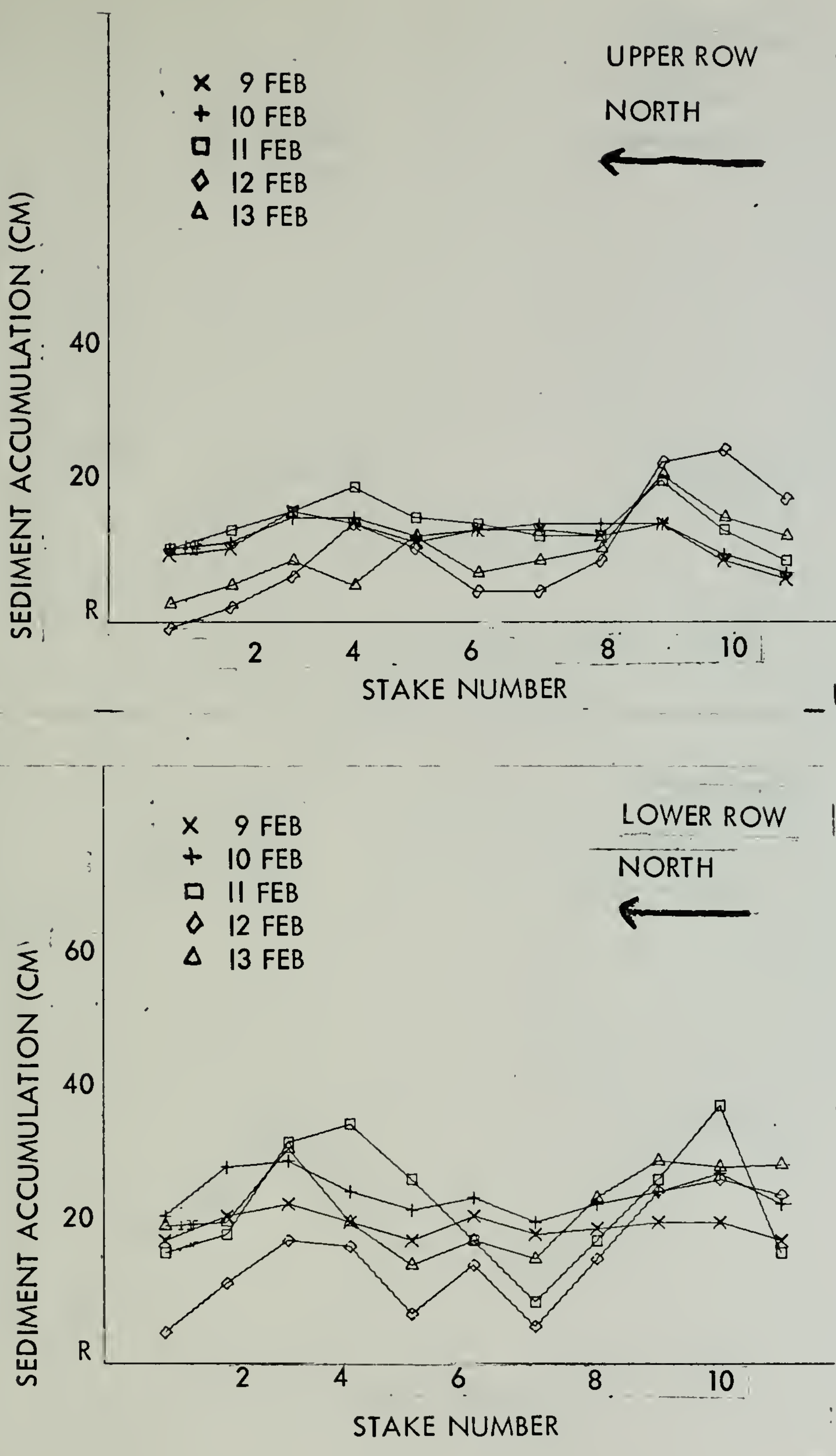
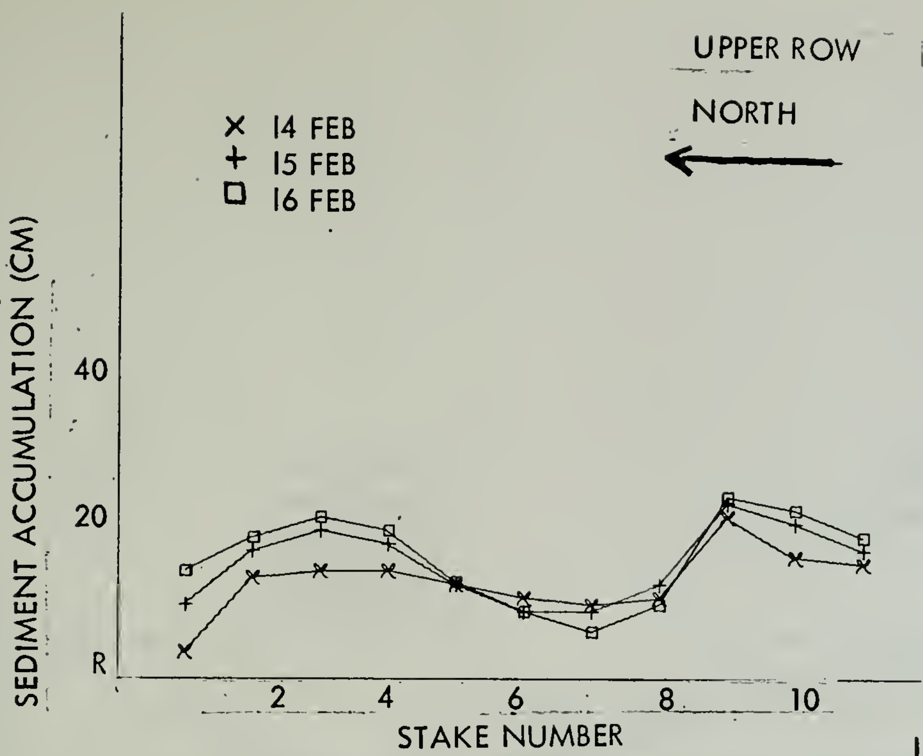


Figure 12. Sediment accumulation profiles for cusp cycle III (9-13 Feb 1974). Stake spacing 15 ft (4.6 m). Depth from reference level (R) to impermeable layer 7 in (18 cm).



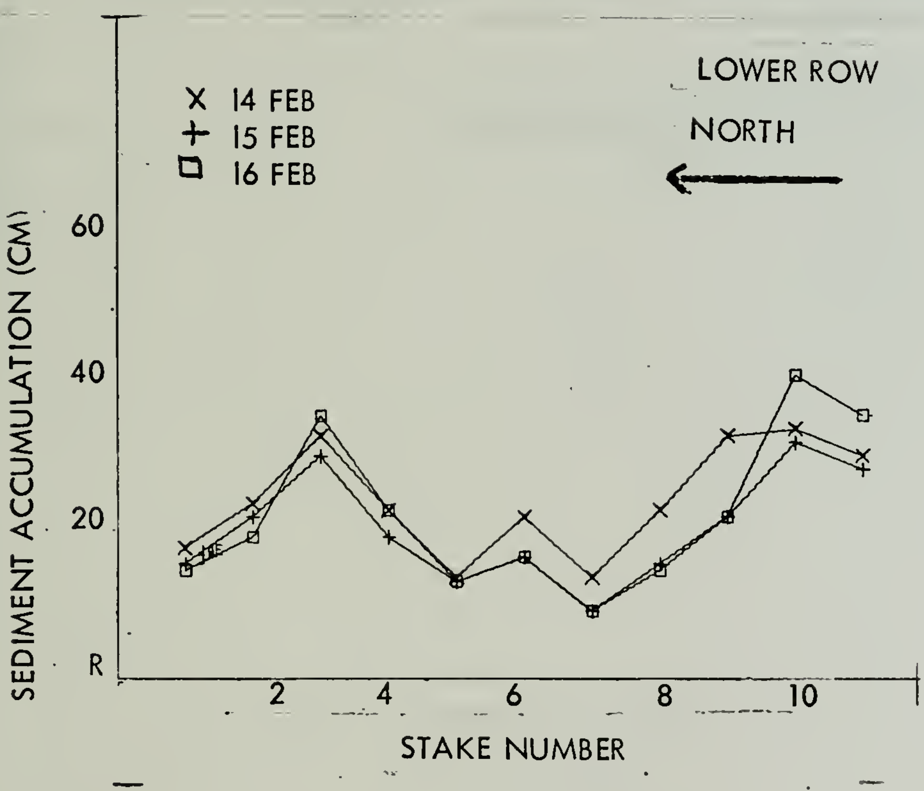


Figure 13. Sediment accumulation profiles for cusp cycle III (14-16 Feb 1974). Stake spacing 15 ft (4.6 m). Depth from reference level (R) to impermeable layer 7 in (18 cm).

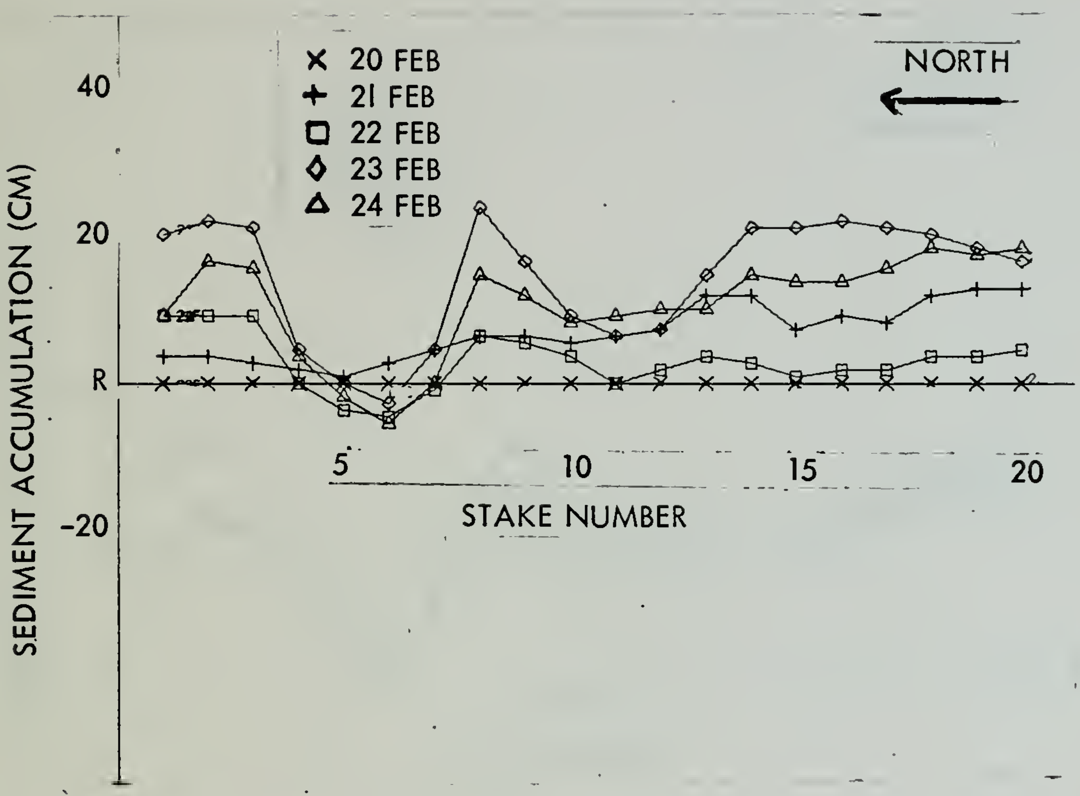


Figure 14. Sediment accumulation profiles for cusp cycle IV (20-24 Feb 1974). Stake spacing 20 ft (6.1 m). Depth from reference level (R) to impermeable layer 10 in (25 cm).

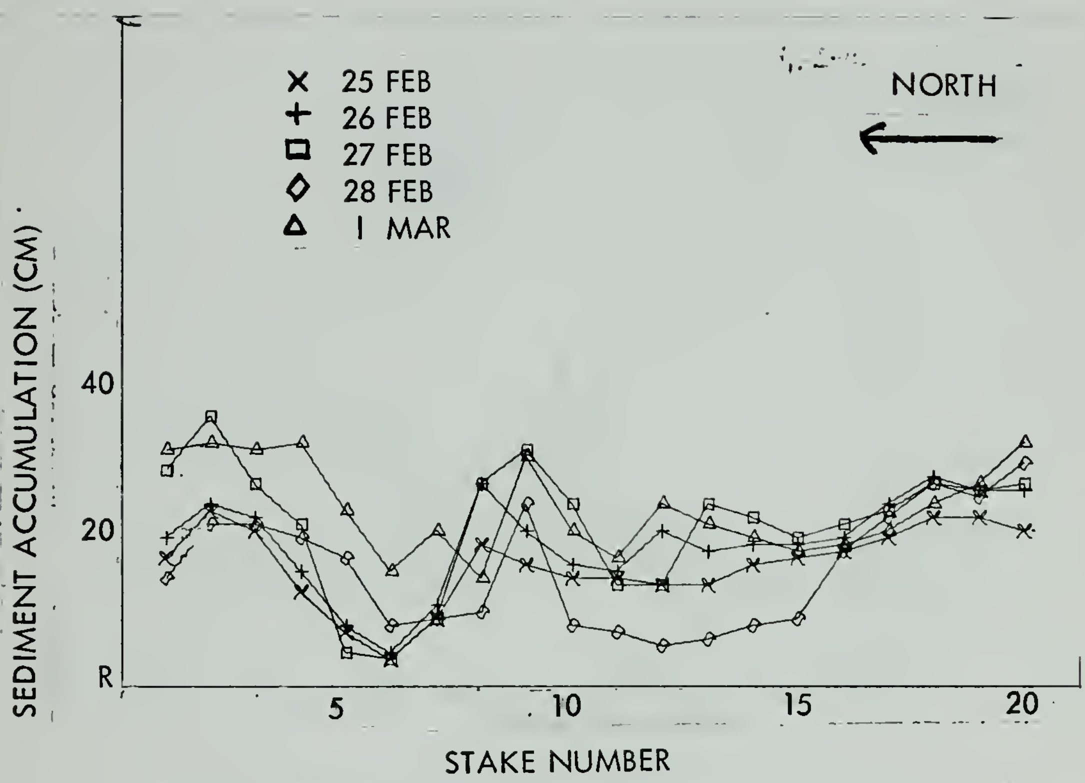


Figure 15. Sediment accumulation profiles for cusp cycle IV (25 Feb - 1 Mar 1974). Stake spacing 20 ft (6.1 m). Depth from reference level (R) to impermeable layer 10 in (25 cm).

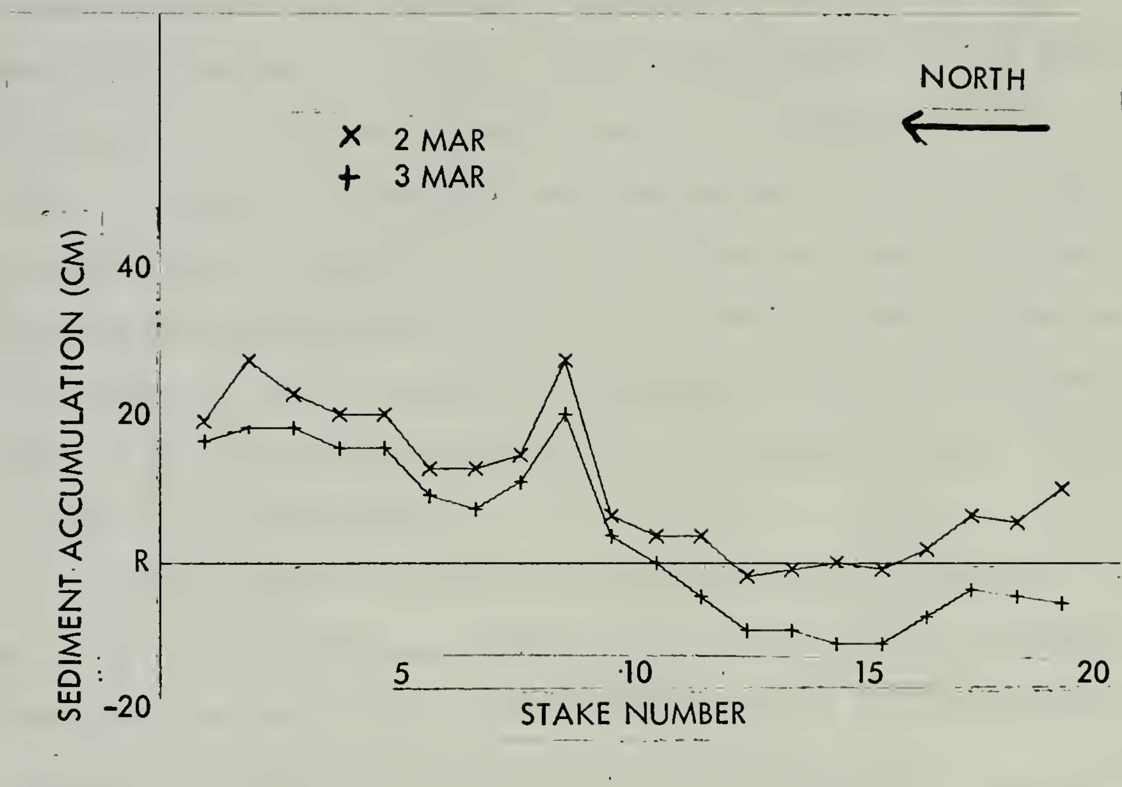


Figure 16. Sediment accumulation profiles for cusp cycle IV (2-3 Mar 1974). Stake spacing 20 ft (6.1 m). Depth from reference level (R) to impermeable layer 10 in (25 cm).

IV. DISCUSSION AND INTERPRETATION

A. CUSP FORMATION

Observations during this experiment indicated that although cusp spacing is a function of several parameters related in a complex manner, certain fundamental conditions must be satisfied in order for cusp formation to proceed. Initially, a smooth, flat beach free from debris is necessary. On occassions when the beach was littered with large amounts of kelp no cusp formation was observed until large waves swept the beach clean. Kelp and debris deposited upon the beach after cusps were present altered the swash pattern with resulting cusp deformation. No evidence was found to support the theories of Jefferson [1899] and Evans [1938] requiring seaweed, debris, or the presence of sand ridges to initiate cusp development.

A uniform angle of beach slope was found to exist for the entire period of the experiment. An average beach slope of 3.6° was present during the four cusp cycles, and an average slope of 3.5° was observed during the intervening periods when no cusps were present.

A suitable supply of loose, easily transportable sand grains must be present before cusp formation will begin. The erosive action of large storm waves removes this loose sand from the beach until the impermeable layer described by Longuet-Higgins and Parkins [1962] is close to the surface. Redeposition of this eroded material upon the beach provides the sediment for reworking into cusps. According to Sundborg [1956, p 197] particles of fine sand (0.06 - 0.5 mm) are those which are most easily moved. All of the sand samples analyzed in this study fell within this range.

The existence of regular, long-crested, waves incident perpendicular to the beach is essential to cusp development. Oblique wave angles were observed to deform cusps, and large "storm" waves destroyed them completely. Swell waves with a period of 14-16 sec appeared to be coincident with increased cusp spacing.

Cusp formation appeared to begin at preferential locations upon the beach during a period of reduced wave activity following a storm. Whether these locations of accretion were influenced by swash zone topography as indicated by Longuet-Higgins and Parkins [1962] and Flemming [1964] was not conclusively demonstrated. However, on one occasion (21 Feb 1974), the presence of a shallow depression containing small granules 2-4 mm in diameter was noted in the swash zone seaward of the cusp horns. During cusp cycle I, a juvenile cusp was observed to form as a seaward extension of a relic beach cusp. Subsequent wave action modified the cusps developed to conform to existing wave conditions.

The time required for cusps to form varied from 6 - 12 hours to 2 - 3 days, with about 1 day representing a typical case. Simultaneous generation of cusps was never observed during this study. All cusps developed sequentially from an initial embryo horn. Additional cusps were formed after the initial cusp was developed (horn-bay-horn) sufficiently for the "down beach" horn to affect swash patterns beyond it. This pattern can be most easily traced by a study of cusp cycle II (Figure 10). This sequence lasted only 3 days and was terminated abruptly prior to maturation by large storm waves. Initial accretion began on 31 January in the vicinity of stake #8 (Figure 10). Deposition occurred and perturbation of the swash pattern resulted in subsequent

erosion of the embayment. Further deposition on the periphery of the swash resulted in the formation of a second horn near stake #2. On the following day, a layer of fine sand was deposited resulting in a higher profile, but the horn at stake #8 still showed preferential growth.

A consideration of the factors affecting the swash as it flows over the embryo horn will serve to explain the above patterns. As water flows up the rise created by initial accretion, its kinetic energy is dissipated by friction, conversion to potential energy, and by percolation into the sand. Water flowing to either side of the rise must travel proportionately farther in order for the same amount of kinetic energy loss to occur. As discussed earlier, the relative permeabilities are greater on the cusp horns than on the embayments. This results in a reduced capability for erosion on the developing horns. As indicated by Flemming [1964] and Russell and McIntire [1965], the sediment remains in suspension as long as sufficient turbulence is maintained. When energy considerations reduce the turbulence and velocity sufficiently, deposition occurs on all areas of the developing cusp; however, increased percolation on the horn results in preferential deposition of coarser particles. Reduced permeability in the embayment enables the backwash to entrain coarser fractions and return them towards the surf.

The completion of development of the juvenile cusp is a result of perturbation of the swash pattern by the existing horn. The uprush is diverted in sweeping arcs to either side of the horn. Loose material is eroded by the uprush and deposited on the periphery of these arcs, with the finer fractions carried seaward by the backwash. This arcate

pattern results in the formation of a second embryo horn "downstream" to the first, and a complete cusp is then formed. The pattern of water motion present is now as described in Figure 2 and shown in Figures 17 - 18. This is the same pattern observed by Bagnold [1940].

B. GROWTH AND MATURATION OF CUSPS

The growth of the juvenile cusp continues until the capability of the backwash to erode the embayment is negligible. This reduction of erosive potential is enhanced by the interference effect of the two streams of water uniting in the center of the embayment. The cusp spacing during growth is primarily a function of the energy of the waves (a function of wave height) and the wave frequency. If the wave regime remains constant, a resonance effect appears to exist and a significant change in wave height and/or period is required to alter the spacing. Occasionally, when an embayment is too large, streams flowing around the periphery of the embayment will expend considerable energy before uniting [Flemming, 1964], resulting in deposition of a secondary horn in the center of the embayment. This can be seen in Figure 12. A secondary horn can be seen to be developing in the area of stake #6 in the lower row of stakes. This feature prevailed until 13 February when an increase in wave height imported sufficient energy to the uprush to facilitate erosion of the secondary horn. Wave heights subsequently decreased following this period, and the secondary cusp reappeared on 14 February.

The effect of wave angle upon cusp growth can be seen in Figures 8 - 9. In cusp cycles II, III, and IV, the southern most horn was formed first and growth progressed northward. This pattern was begun in cycle I,

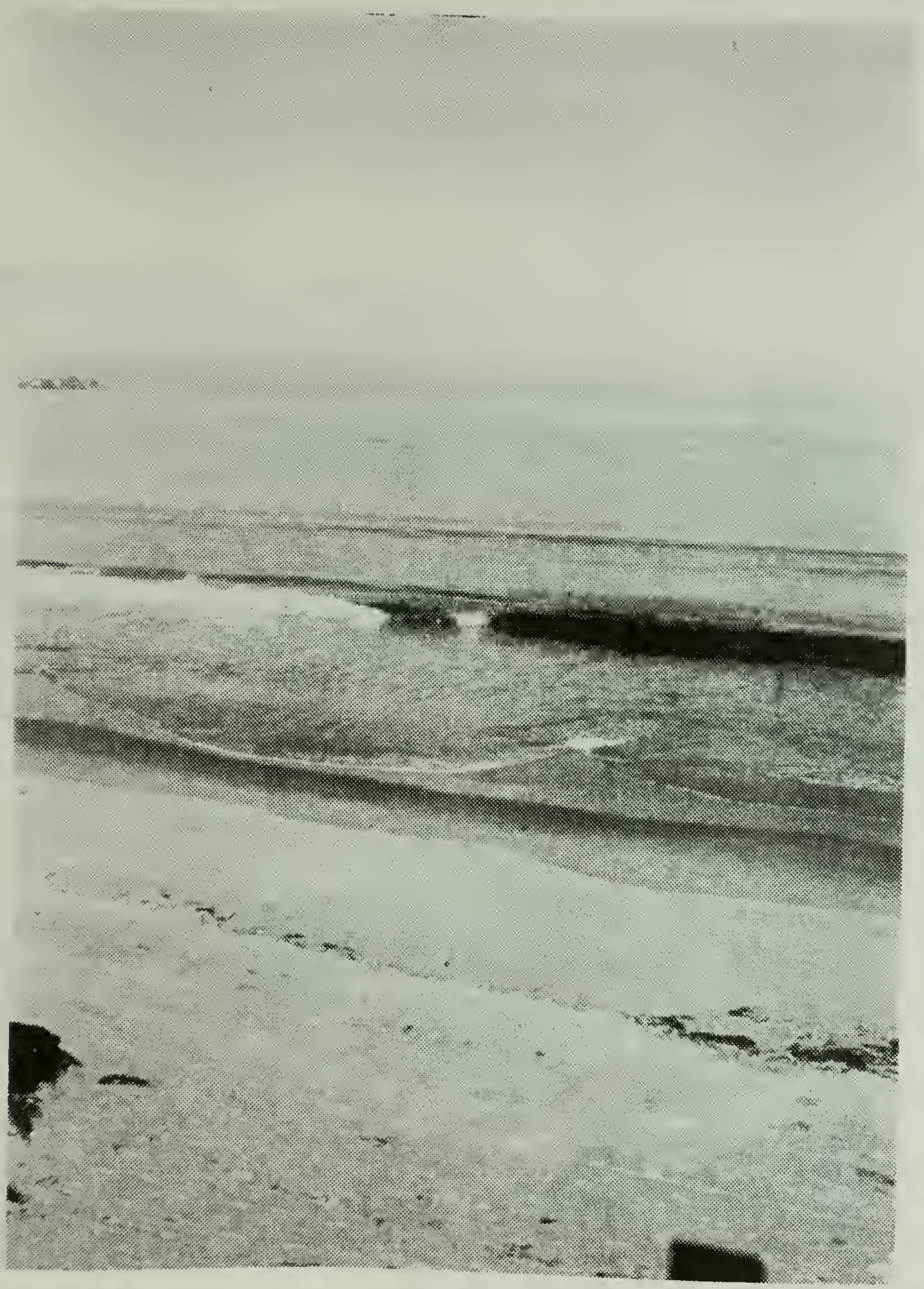


Figure 17. Photograph showing swash patterns related to beach cusps at high water.

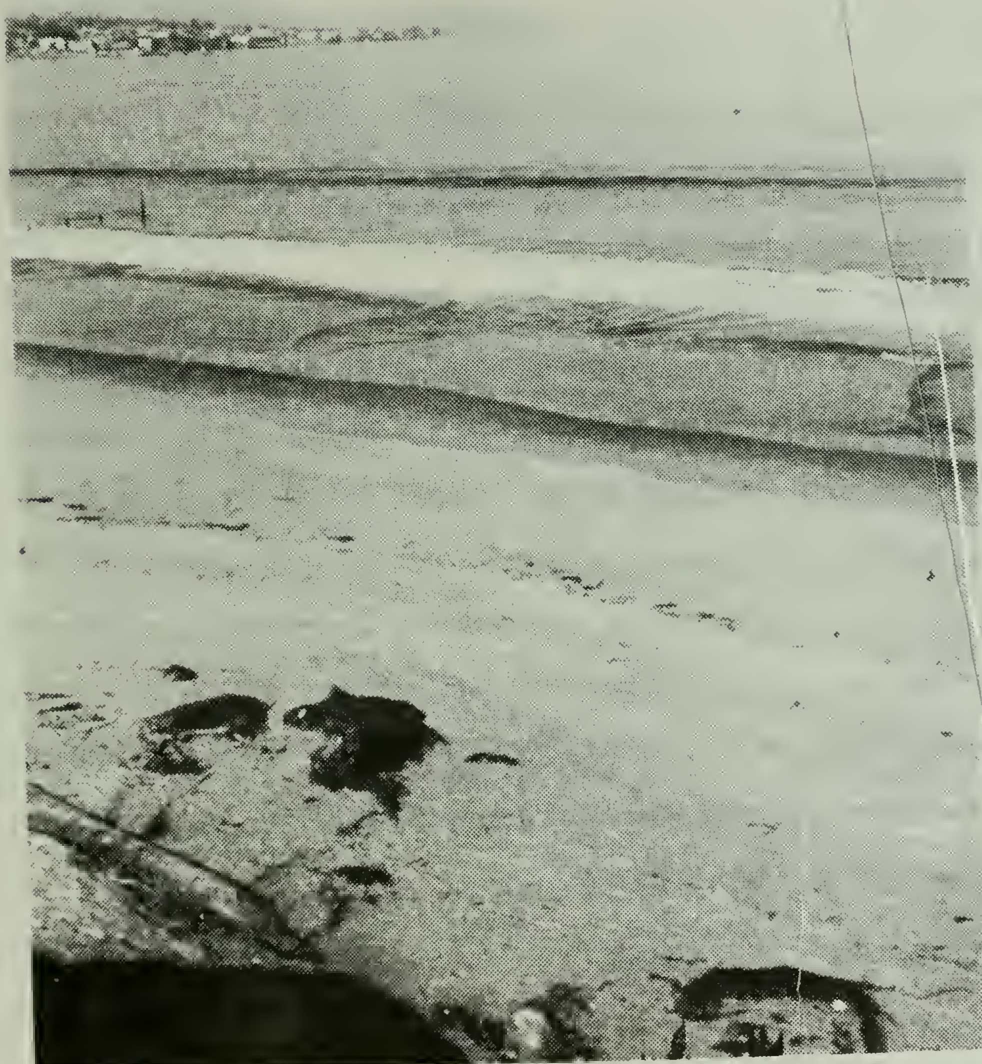


Figure 18. Photograph showing swash patterns related to beach cusps at low water.

but for two days commencing 25 January the wave angle became oblique (approximately 5°). The result was a reversal of the growth pattern with the northern most horn predominating and being the more sharply defined. Wave propagation was again normal to the beach on 27 January, but the sharp resolution of the cusps present in the other cycles was not restored.

During cusp cycle IV an attempt was made to confirm the sequential development of a series of cusps. This experiment can be traced in Figures 14 - 16. A single row of stakes covering 400 ft (122 m) of beach was implanted. Initial development commenced on 21 February, and the first cusp (Cusp A) was well defined by 22 February, spanning the distance between stakes #2 and #8. At this point, the effect of the northern most horn upon the uprush was sufficient to initiate formation of the next cusp in the series. By 24 February, this second cusp (Cusp B) was also well defined (Figure 14), and indications pointed toward the possible development of a third cusp in the series. The period 26 February - 2 March was marked by a fluctuation in wave heights and wave periods (14-16 sec). This is reflected in the fluctuating cusp profile during this period as evident in Figure 15. Although the initial cusp remains as an entity, traces of the second cusp become progressively harder to discern until on 3 March (Figure 16) it can no longer be asserted to be present.

An interesting item with respect to this experiment concerns the grain size comparisons between horn and bay of the second cusp. As indicated in Table I, Cusp B did not exhibit the expected pattern of a coarser horn grain size than in the bay, but rather the reverse. A possible explanation is that fluctuations in wave height and period

during the juvenile stage of development prevented the cusp from becoming stable. The same tendency was initially exhibited on Cusp A, but did not persist.

Once the cusps became mature, changes in the profile were minor. Continuing deposition of fine sand smoothed and rounded the sharp outlines of the juvenile cusps, but very little migration of the reference cusp was observed. Examination of the entire series of profiles reveals quite clearly that cusp formation is a depositional process. Erosion in the embayments occasionally resulted in deepening below the reference level. This reflects sediment which had accumulated prior to insertion of the stakes.

No attempt was made during this experiment to observe the presence of edge waves, although it was recognized that edge waves could be important in the cusp formation process. Because wave period and beach slope were relatively constant during a given cusp cycle, it is reasonable to assume that edge wave numbers would be relatively constant.

C. DECAY OF CUSPS

Cusps were observed to be destroyed primarily by the action of wind waves or by large breakers. The influence of tidal cycles was felt to be minimal during this experiment. Storm surges resulted in the removal of nearly all sediment from the beach and concomitant destruction of cusps. Destruction of cusps by storm waves took place within a 24 hour period in each cycle. These large waves removed the measurement stakes and necessitated insertion of new stakes prior to further measurement.

V. SUMMARY AND CONCLUSIONS

The formation of beach cusps is a complex process marked by the subtle interaction of many factors. The existence of a given set of conditions does not guarantee the formation of cusps, but certain conditions have been discovered to be preferential. A smooth, uniformly sloping beach, free of kelp and other debris is essential. It is this smooth beach that provides a pavement level upon which loose, permeable, and easily transportable sand is deposited. Waves of sufficient height to impart the necessary energy to rework this accumulated sediment then begin to shape the cusps. A nearly zero breaker angle and a regular wave period are necessary conditions during these early stages of cusp development.

The formation of cusps is a depositional process. Initially, an area of accretion on the beach provides a preferential site on which the action of the uprush is concentrated. Deposition in this area results in a perturbation in the flow pattern of the swash. Sediment is removed from the embayment and redeposited along the periphery of the swash arc resulting in the formation of a second horn. Although the formation of the embayment is an erosional process in that sediment is removed, the original impermeable layer provides a base level for the depth of the embayment. Cusp formation is therefore a reworking of sediment deposited rather than erosion of a beach.

The development of a series of cusps is a sequential process. The formation of each successive horn provides the alteration of swash flow pattern necessary for the formation of subsequent embayments and horns. This process will continue as long as beach conditions and the existing wave regime are favorable.

The deposition of coarser sediment fractions on the cusp horns is reflected by increased relative permeabilities at these locations. Continuing deposition during early development stages permits increased percolation which results in a proportionally greater loss of kinetic energy on the horns, further contributing to the formation process.

The spacing between one cusp horn and the next is primarily a function of wave height (energy) and wave period. Uniform spacing is the result of a constant wave regime during the formative process. This is certainly an over simplification of the role of the many factors involved in cusp formation and spacing. This author believes that a height limit exists above which breaker height is the most dominent factor in terms of energy considerations. However, if waves during the initial phases of development are small, the relative importance of factors such as sediment grain size and beach slope is magnified.

Swell waves with a period of 14-16 sec appeared to enhance cusp development by a resonance effect. Each wave completes its sculpturing of the cusp before the next wave arrives. Although not observed during this experiment, it is the opinion of this researcher that extreme variations in wave period would result in modification of the cusp spacing. Extremely short period waves could be expected to interfere with the action of their predecessors on the beach.

Once cusps are established upon a beach little spatial migration occurs. The deposition of additional fine sediment may result in smoothing of the cusp outline, and small changes in breaker angle can cause asymmetry. A significant change in the wave regime is required to effect major changes in spacing or profile. A two-fold increase

in wave height was observed to result in a 2 ft (0.6 m) change in cusp spacing.

Large wind waves were observed to be the major influence in the destruction of cusps. These waves were observed to sweep the beach clean and restore it to its original pavement level. Once this condition was achieved, redeposition of sediment under reduced wave conditions was necessary before cusps would form again. Waves breaking directly upon the cusps or the action of spring tides and storm surges also could result in the destruction of cusps.

VI. RECOMMENDATIONS

Further research is required to extend the conclusions for specific sites and to develop a generalized equation for cusp formation. This will require study at a variety of sites. Emphasis should be directed toward the selection of experimental sites which exhibit the maximum possible range of variance in the measured parameters. This will greatly enhance the capability of multiple regression techniques for data analysis.

To satisfy the above conditions, future experiments over expanded time scales will be required. Sufficient time should be alloted to allow observation at several sites. Data collection should only be during those periods during which significant changes are taking place. An observational/data collection period of 3 - 6 months is recommended. An expanded time frame would also allow the time necessary for sediment analysis to be performed in 1/4 - Φ increments.

The use of automatically recording, electronic wave gauges of the resistance or capacitance type is also recommended to ensure greater accuracy in wave height measurements. However, the use of such equipment will require considerable effort to ensure adaquate protection against vandalism and natural damage.

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